

VERITAS observation of Markarian 421 flaring activity

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Abstract: Markarian 421 is one of the brightest BL-Lac objects in γ -rays in the northern hemisphere. Because of its brightness, the source has been the focus of several coordinated multi-wavelength (MWL) campaigns designed to study the physical processes responsible for the non-thermal continuum emission. The blazar monitoring program of VERITAS recently received a ToO during a strong flaring event by Markarian 421 in February 2010. The source was seen at flux level of approximately 8 Crab units and exhibited spectral evolution and variability features. A multi-wavelength campaign with other MWL partners was undertaken. Results on past and recent flaring events are presented.

Keywords: TeV IACT Cherenkov gamma-ray Mrk 421

1 Introduction

Blazars are a subclass of active galactic nuclei (AGNs) presenting rapid variability and non-thermal emission across nearly the entire electromagnetic spectrum, implying that the observed photons originate within highly relativistic jets oriented very close to the observers line of sight [1]. Various models have been proposed to account for the broadband spectral energy distributions (SEDs) observed in very high energy (VHE: $E > 100$ GeV) blazars, which typically display two major components peaking at different energies: the lower-energy peak (10^{13} Hz $\lesssim E_{\text{peak}} \lesssim 10^{19}$ Hz) is due to synchrotron emission by highly relativistic electron and positrons, and the higher-energy component is due to inverse-Compton (IC) scattering of the synchrotron photons by these relativistic e^+e^- [2, 3]. Hadronic interactions producing neutral pions which decay into photons [4], and synchrotron emission from protons [5] are also possible scenarios for the high-energy component of blazars.

Observationally, blazars undergo both major outbursts on long time scales and rapid flares on short time scales, most prominently at keV and TeV energies. During some outbursts, both of the SED peaks have been observed to shift toward higher energies in a generally correlated manner [6]. The correlation of the variabilities at keV and TeV energies (or lack thereof) during such outbursts has aided in refining the emission models. In addition, rapid, sub-hour flaring activity is interesting as it provides direct constraints on the size of the emission region.

BL-Lac objects are a particular class of blazars with the featureless non-thermal continuum dominating over the

discrete emission. Markarian 421 (Mrk 421; 1101+384), at a redshift of $z = 0.031$, is a high-frequency peaked (HBL: $E_{\text{peak}} \gtrsim 10^{17}$ Hz) BL-Lac object that historically shows intense and rapid flaring episodes. Its flaring activity is particularly interesting for two reasons: 1) its relativistic high flux facilitates the characterization of its spectral and temporal features; 2) frequent flaring activity permits the time evolution of the low and high portions of the SED to be studied. Therefore Markarian 421 has been the focus of coordinated MWL observational campaigns, from optical to the γ -ray energy band. These campaigns are triggered by the observation of flares by any of the MWL partners monitoring the source.

Here we report results from past and recent observation of Markarian 421 flaring episodes.

2 VERITAS Observation

2.1 The VERITAS Detector

The VERITAS detector is an array of four 12-m diameter imaging atmospheric-Cherenkov telescopes located in southern Arizona [7]. Designed to detect emission from astrophysical objects in the energy range from 100 GeV to greater than 30 TeV, VERITAS has an energy resolution of $\sim 15\%$ and an angular resolution (68% containment) of $\sim 0.1^\circ$ per event at 1 TeV. A source with a flux of 1% of the Crab Nebula flux is detected in 25 hours of observations. The field of view of the VERITAS telescopes is 3.5° . For more details on the VERITAS instrument and the imaging atmospheric-Cherenkov technique, see [8].

2.2 Past observational campaigns of Markarian 421 flaring activity

Markarian 421 has been intensively studied in the past both by VERITAS and by the Whipple 10 m γ -ray telescope. Between 2006 and 2008, Whipple and VERITAS recorded 96 hrs and 47 hrs of data on Markarian 421 respectively. During this campaign, quasi-simultaneous MWL data in radio, optical and X-ray have been taken. Figure 1 shows the combined lightcurve of this long-term MWL campaign. A detailed analysis of the MWL data over this campaign is presented in [13]. Flux variability is found in all bands except in radio. In particular, the X-ray and VHE energy bands are found to be often correlated. Such correlation implies that the particle population responsible for the synchrotron and IC component are the same. Although this correlation is seen as a general trend, it does not necessarily hold true at the level of individual flares. On the other hand, optical/TeV correlation is not found, suggesting that the optical emission might not be dominated by the optical synchrotron component from the jet. The broadband SED is well described by a single zone SSC model and no evidence for flux variability on the time scale of a minute is found.

Our ToO program on Markarian 421 was first triggered in April 2006 by a major outburst from Markarian 421 as detected by regular monitoring of the VHE band by the Whipple 10 m telescope. The program was triggered again in May 2008 by another major outburst from Markarian 421, also detected in the VHE band. Because of observational constraints, in both cases we captured only the decaying portion of the outburst. However, taken together, the two campaigns have produced a significant amount of simultaneous optical/UV, X-ray, and VHE data. During the first April 2006 campaign, Markarian 421 was observed for about 3 hrs with the Whipple 10 m γ -ray telescope, and for about 3 hrs with MAGIC, at energies above 400 and 100 GeV respectively. During the following May 2008 flare, about 2 hrs of observations by VERITAS were obtained. During each of the three VHE observations, truly simultaneous data in optical/UV were recorded with the *XMM-Newton* satellite's Optical Monitor (OM: 170-650 nm) and EPIC-pm detector (EPN: 0.5-10 keV).

The coordinated ToO MWL campaign provided important, and to an extent unexpected, results on the spectral behavior of Markarian 421 [9]. The broadband SED is fitted with the one-zone leptonic SSC model. The best fit to the MWL data set is obtained under the assumption of a pure SSC mechanism without any extra external Compton (EC) component. Surprisingly both 2006 and 2008 data sets show no obvious correlation between X-ray and VHE data, nor between optical/UV and VHE. Clear correlation between optical/UV and X-ray data is nowhere observed. This suggests that the X-ray and VHE photons originate from two distinct electron/positron populations, similar to what was observed during a study of PKS2155-304 [17]. Other sce-

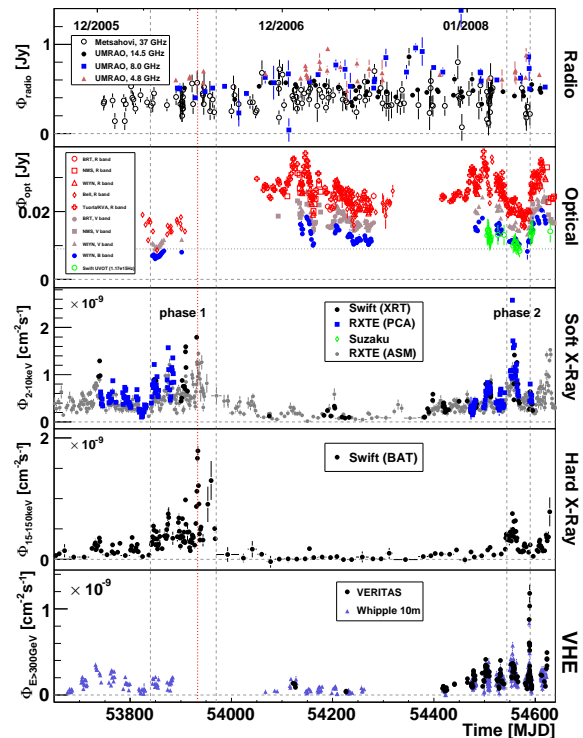


Figure 1: Light curves measured by different experiments in 2006-2008, including extensive VHE observations by Whipple and VERITAS. Two phases of activity appear in the X-ray and TeV bands (phases 1 and 2, grey vertical lines). Phase 1: Maximum of hard X-ray flux (Swift/BAT, red line). Phase 2: Good X-ray/TeV coverage, X-ray observations partly triggered by VERITAS. Figure from [13]

narios that could explain the observed variability patterns include the possibility of an inhomogeneous emission region or hadronic origin of the VHE emission. It is interesting to note that Markarian 421 during this particular flares is clearly behaving very differently here from its typical flaring periods (e.g. [6]), where the X-ray and VHE variabilities are seen to be strongly correlated. Spectral hysteresis patterns are also observed in the X-ray data during the 2006 flare. Although spectral hysteresis has been previously observed in other blazars too, the phenomenon is not fully understood yet. A possible explanation is that spectral hysteresis is produced by the combined effect of three different typical time scales [18]: the duration of the flaring variability t_{var} , the synchrotron cooling time t_{cool} and the particle acceleration t_{acc} . The clockwise hysteresis found in the X-ray data, indicating a lag at lower energies in the X-ray band, coupled with the essentially symmetric shape of the flare in the X-ray light curve seems to indicate that the case with $t_{\text{cool}} \gg t_{\text{var}} \gg t_{\text{acc}}$ is most relevant to this observation.

2.3 February 2010 flaring episode

VERITAS monitored the BL-Lac Markarian 421 from November 2009 to April 2010, taking short snapshots

at irregular intervals, for approximately 20 hours of good-quality effective observation time. The observations have been performed by pointing the telescopes at 0.5° North/South/East/West offset in order to get simultaneous background measurement, with the telescopes operating at an average zenith angle of 17° . On February 17, 2010 VERITAS was alerted by its γ -ray partners that the source was in flaring state. Five hours of data were obtained. Unfortunately, due to technical reasons telescope #1 was unavailable, resulting in a degraded 3-telescopes array observation. The VERITAS flaring event triggered a MWL campaign on the following nights to its X-ray partners [14]. In addition, the VERITAS observation was performed during an X-ray monitoring by the *Swift* X-ray telescope (XRT). XRT recorded about 1 ks of quasi-simultaneous data during the night of the flare. XRT took another 11 ks of data during the following two nights, when Markarian 421 was still in flaring state although at a lower flux level. A total of 22 ks of X-ray data were taken by XRT between February 15, 2010 and March 4, 2010. Finally, the *Fermi* large area telescope (LAT) provided simultaneous observation of the source in the 100 MeV - 100 GeV energy range.

Prior to event selection and background subtraction, all shower images are calibrated and cleaned as described in [10, 11]. Several noise-reducing event-selection cuts are made at this point. Following the calibration and cleaning of the data, the events are parametrized using a moment analysis [12]. From this moment analysis, scaled parameters are calculated and used for the selection of the γ -ray-like events [15, 16]. The event selection cuts are looser than the ones typically used on a Crab-like source (power-law spectrum photon index $\alpha = 2.5$ and 1 Crab Nebula flux level) in order to take advantage of the large statistics in the flux reconstruction.

Top of figure 2 shows the θ^2 plot of the VERITAS data collected the night of the flare. Although in partial-array configuration, VERITAS detected VHE emission from Markarian 421 at the 260σ significance level over 4.9 hr effective observation time. The VHE photon rate is 1.2 Hz, corresponding to ~ 8 times that of the Crab Nebula. The average flux level during the flaring event is about four times the average flux level during the monitoring campaign. A preliminary spectral analysis is done separately for the night of the flare and for the rest of the season. Clear spectral evolution dependent on the flux level is visible, consisting in spectral hardening and increase of the cutoff energy in the high-flux state data.

Figure 3 shows the Markarian 421 nightly lightcurve over the entire season, and for the February 17, 2010 flaring event. During the flaring episode, the source is detected at $> 10\sigma$ statistical significance in any 2 minute bin. A preliminary time-resolved analysis shows significant flux variability on a time scale of ~ 5 -10 minutes. Intra-night variability in the May 2008 outburst from Markarian 421 is observed too, although on a longer time scale [9].

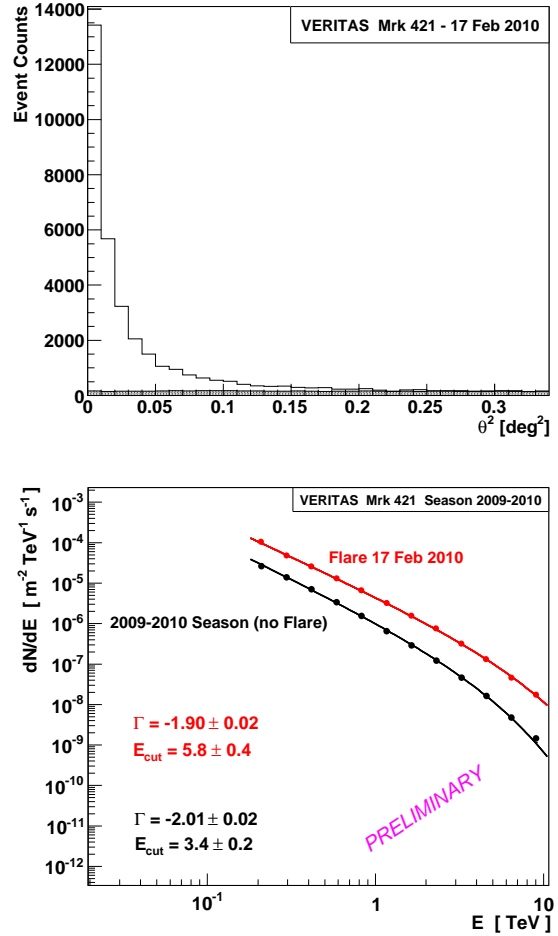


Figure 2: (top) VERITAS θ^2 plot of Markarian 421 data collected during the February 17, 2010 flare. The shaded area is the background, the solid line represents the on-source events. VERITAS detects the HBL Markarian 421 at the 260σ significance level in 4.9 hr effective observation time, corresponding to approximately 8 Crab unit flux. (bottom) VERITAS preliminary spectral analysis of Markarian 421 for two different flux levels: the flare on February 17, 2010 (red dots) and the rest of the 2009-2010 season (black dots).

Conclusions

VERITAS is monitoring the brightest blazars in order to promptly observe and study the physics at work in ultra-relativistic jets. The entire observational campaign on Markarian 421 between 2006 and 2006 provided a detailed characterization of the broadband SED, supporting the one-zone leptonic SSC model as the mechanism responsible for the observed non-thermal continuum emission. The monitoring strategy is successful and resulted in coordinated MWL observational campaigns with optical/UV, X-ray and γ -ray partners. Surprisingly, no obvious correlation between the lower energy (optical/UV and X-ray) and the

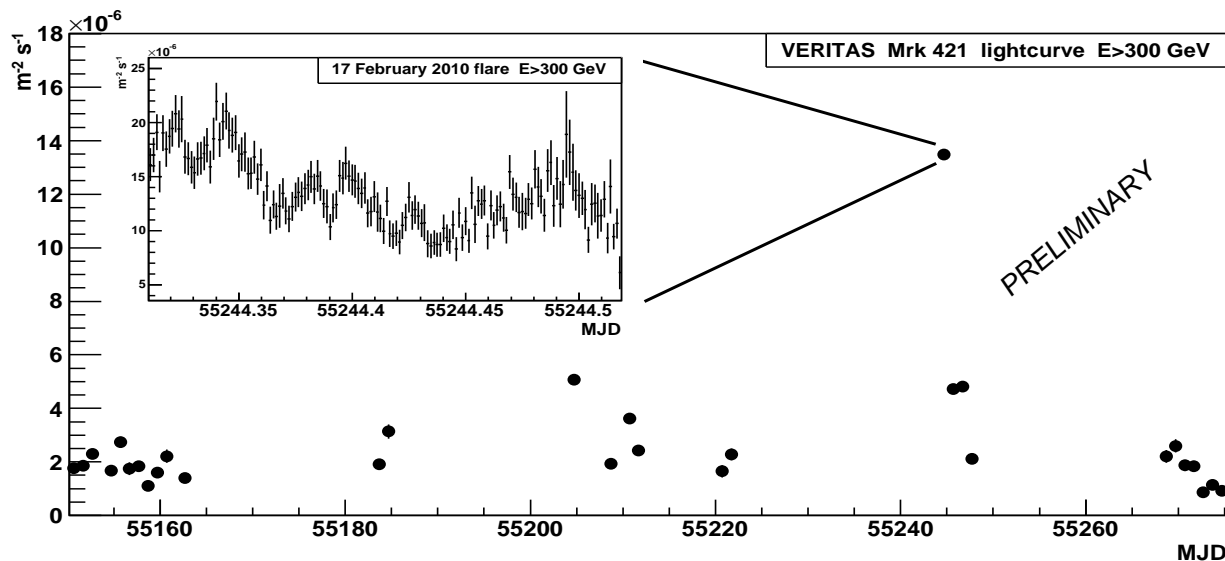


Figure 3: Nightly lightcurve of Markarian 421 during the VERITAS 2009-2010 monitoring campaign. The source is detected at an average flux level of approximately 2 Crab units over the entire season. On February 17, 2010 the source is observed in flaring state at a flux level of ~ 8 Crab units. A zoom of the intra-night 2-minute bins lightcurve of the flaring event is shown. During the flaring event the source is detected at $> 10\sigma$ significance in any of the 2-minute bin, and intra-night variability is seen.

higher energy (VHE) components is seen in the 2006 and 2008 coordinated MWL campaigns. More recently VERITAS observed a big flare on February 17, 2010. The detection of a ~ 8 Crab unit flux from Markarian 421 allows to make time-resolved analysis in order to study intra-night variability, and place constraints on the size and energetics of the physical region responsible for the γ -ray emission. Such a temporal analysis and time-resolved spectral analysis are in progress. A correlated study of the VERITAS VHE observation with the MWL observations provided by LAT and XRT, which will provide insights on the parameterization of the physical models, is still in progress.

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